PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : A61B 8/12 — A1

(11) International Publication Number: WO 94/23652

(43) International Publication Date: 27 October 1994 (27.10.94)

(21) International Application Number: PCT/AU94/00200

(22) International Filing Date: 18 April 1994 (18.04.94)

(30) Priority Data:
PL 8345 19 April 1993 (19.04.93) AU
PL 8488 23 April 1993 (23.04.93) AU

(71) Applicant *(for all designated States except US)*: COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION [AU/AU]; Limestone Avenue, Campbell, ACT 2601 (AU).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: WILSON, Laurence, Sydney [AU/AU]; 11 Monserra Road, Allambie Heights, NSW 2100 (AU). TALHAMI, Habib, Emile [JO/AU]; 18/16 Devonshire Street, Chatswood, NSW 2067 (AU).

(74) Agents: DUNCAN, Alan, David et al.; Davies Collison Cave, 1 Little Collins Street, Melbourne, VIC 3000 (AU).

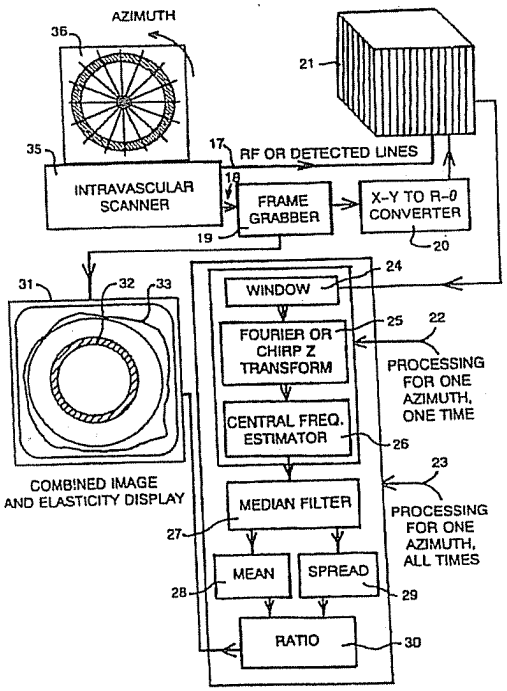
(81) Designated States: AU, CA, GB, JP, US.

Published
With international search report.

(54) Title: TISSUE CHARACTERISATION USING INTRAVASCULAR ECHOSCOPY

(57) Abstract

Calcification of an artery wall and the presence of degenerative plaque on an artery are two symptoms of arterial disease. Ultrasonic echoscopy is used to monitor the presence of calcification of an artery wall. An intravascular transducer (10) at a location within an artery (15) is used to obtain frames of ultrasound during at least one cardiac cycle of a subject. The ultrasound data obtained is processed to produce an indication of the elasticity of the artery wall (12), namely the average fractional deformation of each region of the arterial tissue. This "elasticity" data is displayed simultaneously with an image of the artery wall. The presence of degenerative plaque is determined using intravascular echoscopy and monitoring the frequency content of echoes produced by backscatter from the tisue in the artery wall. The parameter known as the "attenuation slope" of the ultrasound echoes is used as a measure of their frequency content. The values of this parameter are displayed on the conventional grey scale image of the artery cross section at the point of measurement.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria
AU	Australia
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CS	Czechoslovakia
CZ	Czech Republic
DE	Germany
DK	Denmark
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgystan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakhstan
LI	Liechtenstein
LK	Sri Lanka
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SI	Slovenia
SK	Slovakia
SN	Senegal
TD	Chad
TG	Togo
TJ	Tajikistan
TT	Trinidad and Tobago
UA	Ukraine
US	United States of America
UZ	Uzbekistan
VN	Viet Nam

TITLE: "TISSUE CHARACTERISATION USING INTRAVASCULAR ECHOSCOPY"

Technical Field

This invention concerns tissue characterisation. More particularly, it concerns the characterisation of vascular tissue using intravascular echoscopy. One aspect of the present invention is a method and apparatus for the investigation of the elasticity of different regions of the wall of an artery, to detect regions of the arterial wall which have become calcified. The second aspect of the present invention is a measurement technique involving intravascular ultrasound echoscopy, followed by a display of a parameter which has been called the "ultrasound attenuation slope" within the tissue of human arteries. Observation of variations in the ultrasound attenuation slope in different parts of the walls of the arteries assists in the diagnosis of the presence of plaque degeneration in the vascular tissue.

Background to the Invention

It is well known that ultrasound echoscopy may be used for imaging blood vessels from within the vessel, using an intravascular ultrasonic transducer. The ultrasound imaging instruments used in intravascular echoscopy generally have a 360° field of view, and the image of the vessel (usually an artery) is presented in cross-sectional format. Thus, in intravascular echoscopy, all of the ultrasound lines of sight of the transducer usually intersect the vessel wall at, or close to, right angles. The intravascular transducer may be rotated mechanically to

scan the ultrasound lines of sight, but a 360° scan pattern (required to form a complete image, and generally termed an ultrasound "frame") can also be produced by using a transducer having an array of transducer elements, and using phase delays and/or selective activation of the transducer elements to move the ultrasound line of sight around the circularly symmetrical scan pattern.

In primates, one feature of healthy arterial walls is that they are slightly compressed each time the contraction of the heart causes an increase in the internal blood pressure (that is, during systole). The internal diameter of the artery increases and the thickness of the arterial wall is reduced. The amount by which the thickness of the arterial wall is reduced depends upon the stiffness of the vessel wall, and if an area of the arterial wall has become calcified, it will undergo less thinning during systole than a normal, healthy artery wall.

Another feature of healthy arterial tissue is that it contains no plaque (deposits on the artery wall). Plaque, in one of its various types, is caused by arterial disease. Intravascular echoscopy measurements performed at any location within the artery using ultrasound lines of sight in different radial directions will not necessarily exhibit any variation of ultrasound attenuation through the arterial tissue due to the presence of plaque on the artery wall, although the plaque always changes the appearance of the artery in the ultrasound image. Only non-fibrous plaque (that is, degenerative plaque) changes the

ultrasound transmission characteristic in the region of the plaque.

Disclosure of the Present Invention

The prime objective of the first aspect of the present invention is to provide a method and apparatus whereby the elasticity in different parts of diseased arteries can be measured using an intravascular ultrasound transducer.

This objective is achieved by using the intravascular ultrasound transducer to establish the elasticity of individual parts of the artery wall of a subject, as the blood pressure within the artery varies due to the beating of the subject's heart. The elasticity of each part of the artery wall is calculated from ultrasonic data obtained in digital form, during a number of full 360° scans of the ultrasound lines of sight, from echoes received from acoustic discontinuities in the path of a significant number of transmissions of ultrasound beams through the artery wall during at least one cardiac cycle of the subject. The data thus obtained is processed to obtain power spectra for data segments which correspond to respective parts of the ultrasound recording lines of sight (that is, to a respective piece of tissue in the artery wall). The power spectra so obtained at different times for each sampling position are grouped and a characteristic frequency for each group is obtained. The characteristic frequencies are formed into an array of frequencies, which are regarded as an array of numbers. The array of numbers is smoothed, then quantities representing the average values of the numbers and their spread are calculated. The

ratio of these quantities, which is the average fractional deformation of the piece of tissue being investigated, is then calculated and displayed in a suitable form.

Thus, according to the first aspect of the present invention, there is provided a method for use in the detection of calcification of the artery wall of a subject, the method comprising the steps of

(a) positioning an intravascular ultrasonic transducer at a predetermined location in an artery of the subject,

(b) performing, during at least one cardiac cycle of the subject, a plurality of radial ultrasound echoscopy scans of the artery wall at said location by transmitting beams of ultrasound energy and receiving echoes from acoustic discontinuities along respective radial lines of sight separated by equal time intervals, and either (i) recording in digital form the ultrasound A-mode data for each line of sight of said scan, or (ii) computing the image density as a function of distance from the transducer for each line of sight of said scan;

(c) selecting the recorded A-mode data or the image density data for short data segments which correspond to the position of the artery wall;

(d) calculating the power spectrum for each data segment, and grouping the power spectra obtained at different times for each data segment;

(e) determining, for each power spectrum within each group, a characteristic frequency associated with that spectrum;

(f) assigning a representative number to each characteristic frequency obtained by step (e), forming said representative numbers into an array, and smoothing each said array to remove random fluctuations;

(g) for each smoothed array, computing a quantity Q_1 representing the average of the smoothed representative numbers;

(h) for each smoothed array, computing a quantity Q_2 representing the spread of the smoothed representative numbers;

(i) for each smoothed array, computing the ratio Q_2/Q_1, which is the average fractional deformation of the tissue represented by the associated short data segment; and

(j) displaying the values of the ratio Q_2/Q_1;

whereby, from said display of the values of the ratio Q_2/Q_1, variations of the elasticity of the artery wall at said location may be observed.

Usually, at the conclusion of this investigation of the artery wall at one location, the intravascular transducer is moved to another predetermined location in the artery (usually close to the first location) and the method is repeated.

The first aspect of the present invention also encompasses apparatus for use in the detection of arterial wall calcification in a subject, said apparatus comprising an intravascular ultrasonic transducer and associated ultrasonic echoscopy scanning equipment adapted to perform

radial ultrasound echoscopy scanning of the artery wall in the vicinity of a location in an artery of the subject where the transducer has been positioned, by transmitting beams of ultrasound energy and receiving echoes from acoustic discontinuities along respective radial lines of sight which are separated by equal time intervals, said apparatus including:

(a) either (i) recording means for recording in digital form the ultrasound A-mode data for each line of sight of said scan, or (ii) computing means for computing the image density as a function of distance from the transducer for each line of sight of said scan;

(b) computation means for (i) selecting the recorded A-mode data or the image density data for short data segments which correspond to the position of the artery wall, (ii) calculating the power spectrum for each data segment, and grouping the power spectra obtained at different times for each data segment, (iii) determining, for each power spectrum within each group, a characteristic frequency associated with that spectrum, (iv) assigning representative numbers to each characteristic frequency value thus obtained, forming said characteristic numbers into an array, and smoothing each said array to remove random fluctuations, (v) for each smoothed array, computing a quantity Q_1 representing the average of the smoothed representative numbers, (vi) for each smoothed array, computing a quantity Q_2 representing the spread of the smoothed representative numbers, and (vii) for each smoothed array, computing the ratio Q_2/Q_1, which is the

average fractional deformation of the tissue represented by the associated short data segment; and

(c) display means adapted to display the values of the ratio Q_2/Q_1.

The calculation of the power spectra may be performed using a Fourier transform. Alternatively, this calculation may be performed by a chirp Z-transform, which computes frequency components with increased frequency precision over a restricted range of frequencies (determined by the bandwidth of the transmitted beam of ultrasound used to obtain the data being processed).

The characteristic frequency of each power spectrum may be either the frequency corresponding to the maximum power, or the frequency associated with the first moment of the power spectrum.

The smoothing of the characteristic frequency data (the array of representative numbers) is preferably effected with a median filter, which replaces each representative number (characteristic frequency) in a buffer by the median value of (i) itself, (ii) its predecessor in the array, and (iii) its successor in the array.

The quantity Q_2 is preferably the square root of the sum of the squares of the deviations of the smoothed representative number values from the average of those values.

The display of the ratio Q_2/Q_1 is preferably on the display screen that is normally used to display the images generated by the intravascular ultrasound scanner. The display of the ratio may conveniently be a colour overlay on the image, or a graph arranged concentrically around the display.

The prime objective of the second aspect of the present invention is to provide a method and apparatus whereby changes in the properties of vascular tissue, which are associated with degenerative processes in plaque, may be detected and displayed.

This objective is achieved by performing intravascular ultrasound echoscopy of the arterial tissue and monitoring the frequency content of the ultrasound echoes produced by backscatter from the tissue in the arterial wall, including the plaque, and simultaneously displaying, on a conventional intravascular echoscopy display, the variation of frequency content (a parameter termed "the attenuation slope") and information about the size of ultrasonic echoes from the tissue region.

Now it is known that the spectrum of the backscattered ultrasound (that is, the ultrasonic energy that is reflected from acoustic discontinuities in tissue) is affected by the phenomenon known as frequency dependent attenuation. Frequency dependent attenuation is the preferential removal of energy from the higher frequencies of the ultrasound beam generated by the transducer as that beam propagates through the tissue. The change in

frequency content as the ultrasound beam traverses the tissue is measured by recording the echoes from each line of sight in digital form, dividing the recorded echoes into shorter segments, and calculating a number characteristic of the frequency content of the spectrum of the echoes from each region. As shown by L S Wilson, D E Robinson and B D Doust in their paper entitled "Frequency Domain Processing for Ultrasonic Attenuation Measurement in Liver", published in Ultrasonic Imaging, volume 6, pages 278-292 (1984), one suitable measure of the frequency content of ultrasonic echoes is "spectral slope", which is the slope of a straight line fitted by least squares regression to the logarithm of the power spectrum of the ultrasonic echoes. However, other parameters, such as the average frequency of the ultrasonic echoes, may be used equally effectively as an indication of the frequency content of the echoes from each short segment "window" of an ultrasound line of sight. For convenience, the indication of the frequency content, however calculated, will be termed the "spectral characteristic number".

When adopting this technique as part of the present invention, the spectral characteristic number is preferably calculated along every ultrasound line of sight of the transducer during a complete revolution, but in many instances adequate information can be obtained from the spectral characteristic numbers from a subset of the lines of sight (for example, from every second line of sight, or every third line of sight). If the intravascular transducer is translated along the axis of the artery while this technique is being used, calculations of the spectral

characteristic number are carried out over several scan revolutions, and the data obtained refer to a volume of tissue rather than to a two-dimensional area.

The spectral characteristic numbers are considered in small groups of at least two along each ultrasound line of sight. These groups may overlap. The centre of each group is identified with a specific location in the interrogated tissue. A measure of the rate of change with depth of the frequency content is calculated from each group. This measure is calculated as a simple difference if there are only two members in each group, and is preferably calculated as the slope of a least squares regression line of best fit of the frequency content representations of the groups when there are more than two spectral characteristic numbers in each group. Each of these calculated rates of change (now known as the "attenuation slopes") is associated with a particular location in the tissue. Thus the attenuation slope data can be presented on a grid which, in general, will be coarser than the array of pixels comprising the conventional grey scale image.

Thus, according to the second aspect of the present invention, there is provided a method for use in detecting and displaying areas of degeneration of plaque in an artery of a subject, the method comprising the steps of

(a) positioning an intravascular ultrasonic transducer at a predetermined location in an artery of the subject;

(b) recording, in digital form, all of the received echoes of ultrasound energy received from a predetermined number of ultrasound lines of sight during at least

one rotational scan of the lines of sight of the transducer;

(c) selecting a plurality of windows located at a regular spacing down each line of sight and computing, for each window in each line of sight, from the radiofrequency form of the received ultrasound echoes, a spectral characteristic number, the value of which represents the spectral content of echo signals within each window;

(d) for each line of sight, forming the spectral characteristic numbers into groups, each group containing the spectral characteristic numbers in respect of a plurality of adjacent windows, and computing an attenuation slope for each group, the attenuation slope being the local rate of change of the spectral characteristic numbers;

(e) forming, in a digital buffer, an array of pixel values, the value of each pixel in the array corresponding to the average of a number of adjacent attenuation slope values calculated in step (d);

(f) independently of steps (d) and (e), forming, from the radiofrequency data in respect of each window, a conventional image of the artery in which the intensity (brightness) of each pixel in the image is proportional to the amplitude of the ultrasound echoes received from the corresponding piece of tissue; and

(g) determining whether each average attenuation slope pixel value calculated in step (e) exceeds a predetermined threshold value (or a respective one of a predetermined set of threshold values), and if the (or the lowest) threshold attenuation slope value is

not exceeded, displaying the grey scale pixel calculated in step (f) on a conventional output display device of the echoscope; and if the average attenuation slope pixel value exceeds the threshold attenuation slope value (or a respective one of the predetermined set of attenuation slope threshold values), displaying on said output display device a pixel in a form which is different from the normal image pixel display.

The last part of the second aspect of the present invention is the incorporation of the attenuation slope data into the image of a conventional grey scale intravascular echoscope. This instrument produces an image of the vessel that is being examined, using a grey scale representation of echo size. The grey scale image is combined with the attenuation slope image in the following manner. At each grey level pixel in the image, the average of the attenuation slopes at several of the nearest points to that pixel is calculated. If the resulting attenuation slope is less than a predetermined threshold, only the normal grey level of the image is displayed. However, if the predetermined attenuation slope threshold is exceeded, the corresponding pixel is displayed as a colour other than black or white or scales of grey (the normal display hue), with the hue of the colour directly related to the calculated average, in the region of the pixel, of the attenuation slopes. In addition, the brightness of the display is made to be proportional to the grey scale level corresponding to that pixel in the conventional grey scale display. Thus the attenuation slope information is

combined with the grey scale information in a single echoscope display.

This type of display can be used in the detection of areas of degenerative plaque because such areas have a higher attenuation slope than other vascular tissue. With suitable setting of a number of attenuation slope thresholds, such areas will be displayed as coloured regions on an otherwise grey scale image. Because the brightness of the coloured area is modulated by the underlying grey scale, simultaneous display of both the attenuation slope and the echo size at a region of tissue is achieved.

Preferably, several colour hues will be used in the display, each indicating when a respective predetermined threshold of attenuation slope value has been exceeded. However, in a simple (but nevertheless effective) implementation of the present invention, only one colour (hue), in addition to the normal grey level display colour, may be used.

The second aspect of the present invention also encompasses apparatus for detecting and displaying areas of degenerative plaque in an artery of a subject, the apparatus comprising:

(a) reception means for receiving and recording, in digital form, radiofrequency echo signals of ultrasound energy received, by an intravascular ultrasonic transducer that has been positioned at a predetermined location in an artery of a subject,

following transmission of ultrasound by said transducer along a predetermined number of lines of sight;

(b) selection means for selecting a plurality of windows located at a regular spacing down each line of sight and computing, for each window in each line of sight, from the radiofrequency form of the received ultrasound echoes, a spectral characteristic number, the value of which represents the spectral content of echo signals within each window;

(c) computation means for (i) forming the spectral characteristic numbers for each line of sight into groups, each group containing the spectral characteristic numbers in respect of a plurality of adjacent windows, and (ii) computing the attenuation slope for each group;

(d) a digital buffer adapted to receive data from said computation means and to form therefrom an array of pixel values, the value of each pixel in the array corresponding to the average of a number of adjacent attenuation slope values calculated in said computation means;

(e) imaging means for forming, from the radiofrequency data in respect of each window, a conventional image of the artery in which the intensity (brightness) of each pixel in the image is proportional to the amplitude of the ultrasound echoes received from the corresponding piece of tissue; and

(f) comparison means, for determining whether each average attenuation slope pixel value calculated in said digital buffer exceeds a predetermined threshold value

(or a respective one of a predetermined set of threshold values), and if the (or the lowest) threshold attenuation slope value is not exceeded, displaying the grey scale pixel calculated by said imaging means on a conventional output display device of the echoscope; and if the average attenuation slope pixel value exceeds the threshold attenuation slope value (or a respective one of the predetermined set of attenuation slope threshold values), displaying on said output display device a pixel in a form which is different from the normal image pixel display.

For a fuller understanding of the present invention, an embodiment of each aspect of the invention, provided by way of example only, will now be described with reference to the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a schematic diagram of an intravascular ultrasonic transducer which is positioned within an artery containing a region of calcified artery wall, during diastole.

Figure 2 depicts the components and features of Figure 1 during systole.

Figure 3 is a partly schematic, partly block diagram, illustration of one form of apparatus for monitoring the elasticity of an artery wall.

Figure 4 is a partly schematic, partly block diagram illustration of intravascular ultrasonic echoscopy equipment, modified in accordance with the second aspect of the present invention to display regions of degenerative plaque in an artery wall.

Detailed Description of the Illustrated Embodiments

Figure 1 shows, schematically, an intravascular ultrasonic transducer 10 positioned within an artery 15 having a substantially uniform thickness of its wall 12 during diastole. Samples of lines of sight 13 are shown intersecting the artery wall 12 substantially at right angles. The lines of sight 13 are the directions in which ultrasonic energy from the transducer 10 is directed, and along which echoes of that ultrasonic energy are received from acoustic discontinuities. The received echoes are used to form an ultrasonic image. Only a representative number of the lines of sight are shown in Figure 1.

Figure 2 illustrates the changes that occur to the arrangement shown in Figure 1 later in the cardiac cycle, when the condition of the artery 15 changes from diastole to systole. The blood pressure within the artery has increased and the internal diameter of the artery has increased. The thickness of the arterial wall 12 has been reduced except at the region 14. In the region 14, the artery wall has been stiffened as a result of calcification. (In practice, the regions of an arterial wall which have become calcified undergo less thinning than a normal, healthy arterial wall during systole, rather than - as shown in Figure 2 - no thinning at all.)

Apparatus to perform the method of the first aspect of the present invention is shown, partly in block diagram form, in Figure 3. Although this apparatus is shown in Figure 3 as a separate module from the conventional intravascular scanner 35 (which produces the image shown schematically on display 36), it may be incorporated into a conventional intravascular echoscope.

To investigate the elasticity of the artery wall of a subject, using the apparatus shown in Figure 2, data is obtained by sequentially scanning through the ultrasonic lines of sight during at least one cardiac cycle of the subject. This data consists of lines of sight ultrasound echoes data, in digital form. It may be obtained directly from the received echoes of each line of sight, as radio frequency data, through a data path 17 connected to the receiver circuits in the scanner. Alternatively, it may be calculated from images which have been formed in the conventional scanner 35, extracted through a data path 18.

Although the data obtained by the latter method has a reduced quality compared to data obtained directly from the receiver circuits of the scanner, it is more convenient to use the images in the scanner when the apparatus form of the present invention is an independent module which is to be connected to an essentially unmodified intravascular scanner. It requires a frame grabber 19 which converts images in television video form into digitally stored images. The output of the frame grabber 19 is connected to a module 20 which converts the video frame image into lines of sight data (that is, into data representing

one-dimensional arrays of brightness calculated along lines of sight radiating at equal angular intervals from the location of the transducer in the images). Those proficient in this art will recognise that module 20 acts as an x-y to r-θ conversion module.

The lines of sight data are stored in a memory 21 in such a way that they may be accessed according to the three indexing variables depth (that is, distance from the transducer), azimuth (that is, the direction in which the line of sight is pointing) and time (that is, from which ultrasound frame the data was recorded). In general, it will be necessary to record all data before processing it.

The data is processed by a stage 24 which windows in depth so that only data from the artery wall is analysed. It is possible to have (i) a plurality of windows along one line of sight to measure deformations at different depths within the artery wall, (ii) a single window defining the artery wall, or (iii) a window which effectively includes the whole of the data. The following description refers to an embodiment of the invention in which a single window is used for each azimuth position.

Each windowed data segment is transformed using a Fourier or Chirp Z transform stage 25 to produce a power spectrum over a range of frequencies. This range of frequencies is chosen to include most of the energy present in the original line of sight. The next stage (26) performs the calculation of a measure of the dominant frequency present in the spectrum.

The processing within the combination of stages 24, 25 and 26 (shown as box 22 in Figure 3) is repeated for every data frame, so that the time evolution of the data segment is analysed. The data output from box 22 consists of a one-dimensional array of numbers, each of which represents a characteristic frequency for a different ultrasound frame. A median filter 27 applied to the buffer removes apparent frequency shifts not associated with tissue deformations. The operation of the median filter 27 has been described above.

The two modules 28 and 29 compute an average Q_1 and a measure of spread Q_2 (such as a root mean square), respectively, of the smoothed array of frequencies output from the median filter 27 for each line of sight ultrasound frame. A divider module 30 computes the ratio of the spread to the mean value, Q_2/Q_1, which represents the variation in fractional deformation of the tissue. If the basic data has been obtained over two or more cardiac cycles of the subject, improved averaging will be achieved.

In the arrangement shown in Figure 3, the ratio Q_2/Q_1 is computed for each azimuthal position, and for each window along the line of sight if a plurality of windows has been employed for each line of sight.

At the completion of the calculation of Q_2/Q_1 for each location, a special display 31 shows both the conventional ultrasound image 32 (which may be selected from the images recorded in the frame grabber) and the deformation of the artery wall for each position where it has been calculated.

This deformation display may be any one of a number of possible forms, such as a graph 33 of deformation arranged in a concentric fashion around the image of the vessel, or the application to the image 32 of colours whose hue or saturation corresponds to the amount of deformation.

Figure 4 shows an intravascular ultrasonic transducer 41 located within an artery 42 and producing an image in the scan plane 43. A typical ultrasound line of sight 44 is shown. The ultrasonic echoes 45 from acoustic discontinuities in the path of the beam transmitted along each line of sight in a complete (360°) revolution (scan) of the beam(s) produced by the transducer 41 are recorded in digital form, at a sufficiently high sampling rate that they are also recorded in radiofrequency form. The echoes 45 from each line of sight 44 are broken into short segments and the data in each segment are multiplied by a suitable window 46 (such as a Hamming window) in module 420. Each windowed data segment passes through a processor 421 which calculates the Fourier transform of the data segment and converts the result to a logarithmic power spectrum form, of which a sequence of six successive spectra are shown at 47. A further module 422 calculates the slope of a straight line 48 of best fit to each of the power spectra. The slope of the straight line 48 is the "spectral slope" or a "spectral characteristic number" of the data from its associated window.

The array of spectral slopes is then divided (in module 423) into groups of two or three and a series of lines of best fit 49 are calculated. The slopes of these lines 49 are the "attenuation slopes" referred to earlier in this specification. These attenuation slopes pass through a

scan converter module 424 which calculates the position in space corresponding to each attenuation slope computed by the spatial gradient module 423. The scan converter module 424 also smooths the result by replacing each value by the average of itself and a group of neighbouring values. Because the value of each attenuation slope is calculated on a coarser grid than that normally used for imaging, missing values have been calculated by interpolation between the attenuation slope values which are calculated by the above method.

The result of these calculations is a two-dimensional array of numbers, the value of each of which corresponds to the local attenuation slope of the tissue, shown in the drawing as grey levels in an image 410. However, it should be noted that these grey levels are not actually displayed when the illustrated embodiment of the invention is used.

The radiofrequency echoes also pass through a module 411 which computes a conventional grey scale image from the ultrasonic echoes. The scan converter stage 412 used in this processing computes grey scale values (based on echo size), using the same grid as the attenuation slope image. The image produced by the output from the module 412 is shown as image 413, but the image 413 is not necessarily displayed when the illustrated embodiment of the invention is used.

A combined image 414 is formed from the grey scale image 413 by calculating a new coloured pixel value at each location. The hue (colour) of each pixel in the combined image 414 indicates whether the attenuation slope value determined for the corresponding tissue location is above,

or below, a threshold value (or one of a series of threshold values). The brightness (intensity) of each pixel in the combined image 414 is calculated from the grey scale image 413. The user of the illustrated equipment may be given the option of viewing the grey scale image 413, the combined coloured image 414, or both of these images at the same time in a side-by-side format.

The presence of a colour, other than the normal display grey values, in the image 414 provides an immediate indication of the presence of degenerative plaque in the vascular tissue which is imaged by the intravascular echoscopy equipment.

Those familiar with intravascular ultrasonic echoscopy will appreciate that variations and modifications of the illustrated and described embodiments of the two aspects of this invention may be made without departing from the present inventive concepts.

CLAIMS

1. A method for use in the detection of calcification of the artery wall of a subject, the method comprising the steps of

(a) positioning an intravascular ultrasonic transducer at a predetermined location in an artery of the subject,

(b) performing, during at least one cardiac cycle of the subject, a plurality of radial ultrasound echoscopy scans of the artery wall at said location by transmitting beams of ultrasound energy and receiving echoes from acoustic discontinuities along respective radial lines of sight separated by equal time intervals, and either (i) recording in digital form the ultrasound A-mode data for each line of sight of said scan, or (ii) computing the image density as a function of distance from the transducer for each line of sight of said scan;

(c) selecting the recorded A-mode data or the image density data for short data segments which correspond to the position of the artery wall;

(d) calculating the power spectrum for each data segment, and grouping the power spectra obtained at different times for each data segment;

(e) determining, for each power spectrum within each group, a characteristic frequency associated with that spectrum;

(f) assigning a representative number to each characteristic frequency obtained by step (e), forming said representative numbers into an

array, and smoothing each said array to remove random fluctuations;

(g) for each smoothed array, computing a quantity Q_1 representing the average of the smoothed representative numbers;

(h) for each smoothed array, computing a quantity Q_2 representing the spread of the smoothed representative numbers;

(i) for each smoothed array, computing the ratio Q_2/Q_1, which is the average fractional deformation of the tissue represented by the associated short data segment; and

(j) displaying the values of the ratio Q_2/Q_1;

whereby, from said display of the values of the ratio Q_2/Q_1, variations of the elasticity of the artery wall at said location may be observed.

2. A method as defined in claim 1, in which the calculation of the power spectra is performed using a Fourier transform.

3. A method as defined in claim 1, in which the calculation of the power spectra is performed by a chirp Z-transform, which computes frequency components with increased frequency precision over a restricted range of frequencies, said range of frequencies being determined by the bandwidth of the transmitted beam of ultrasound used to obtain the data being processed.

4. A method as defined in claim 1, claim 2 or claim 3, in which the characteristic frequency of each power spectrum is either the frequency corresponding to the

maximum power or the frequency associated with the first moment of the power spectrum.

5. A method as defined in any preceding claim, in which the smoothing of the array of representative numbers is effected with a median filter, which replaces each representative number in a buffer by the median value of (i) itself, (ii) its predecessor in the array, and (iii) its successor in the array.

6. A method as defined in any preceding claim, in which the quantity Q_2 is the square root of the sum of the squares of the deviations of the smoothed representative numbers from the average of the representative numbers.

7. A method as defined in any preceding claim, in which the display of the ratio Q_2/Q_1 is on a display screen that is normally used to display the images generated by the intravascular ultrasound scanner, said display of the ratio Q_2/Q_1, being either a colour overlay on the image, or a graph arranged concentrically around the display.

8. Apparatus for use in the detection of arterial wall calcification in a subject, said apparatus comprising an intravascular ultrasonic transducer and associated ultrasonic echoscopy scanning equipment adapted to perform radial ultrasound echoscopy scanning of the artery wall in the vicinity of a location in an artery of the subject where the transducer has been positioned, by transmitting beams of ultrasound energy and receiving echoes from acoustic discontinuities

along respective radial lines of sight which are separated by equal time intervals, said apparatus including:

(a) either (i) recording means for recording in digital form the ultrasound A-mode data for each line of sight of said scan, or (ii) computing means for computing the image density as a function of distance from the transducer for each line of sight of said scan;

(b) computation means for (i) selecting the recorded A-mode data or the image density data for short data segments which correspond to the position of the artery wall, (ii) calculating the power spectrum for each data segment, and grouping the power spectra obtained at different times for each data segment, (iii) determining, for each power spectrum within each group, a characteristic frequency associated with that spectrum, (iv) assigning representative numbers to each characteristic frequency value thus obtained, forming said representative numbers into an array, and smoothing each said array to remove random fluctuations, (v) for each smoothed array, computing a quantity Q_1 representing the average of the smoothed representative numbers, (vi) for each smoothed array, computing a quantity Q_2 representing the spread of the smoothed representative numbers, and (vii) for each smoothed array, computing the ratio Q_2/Q_1, which is the average fractional deformation of the tissue represented by the associated short data segment; and

(c) display means adapted to display the values of the ratio Q_2/Q_1.

9. Apparatus as defined in claim 8, in which said display means is adapted to present the ratio Q_2/Q_1 in graphical form around a conventional image of the artery.

10. Apparatus as defined in claim 8, in which said display means is adapted to present the ratio Q_2/Q_1 as a colour overlay on a conventional image of the artery.

11. A method for use in detecting and displaying areas of degeneration of plaque in an artery of a subject, said method comprising the steps of

(a) positioning an intravascular ultrasonic transducer at a predetermined location in an artery of the subject;

(b) recording, in digital form, all of the received echoes of ultrasound energy received from a predetermined number of ultrasound lines of sight during at least one rotational scan of the lines of sight of the transducer;

(c) selecting a plurality of windows located at a regular spacing down each line of sight and computing, for each window in each line of sight, from the radiofrequency form of the received ultrasound echoes, a spectral characteristic number, the value of which represents the spectral content of echo signals within each window;

(d) for each line of sight, forming the spectral characteristic numbers into groups, each group

containing the spectral characteristic numbers in respect of a plurality of adjacent windows, and computing the attenuation slope for each group, the attenuation slope being the local rate of change of the spectral characteristic numbers;

(e) forming, in a digital buffer, an array of pixel values, the value of each pixel in the array corresponding to the average of a number of adjacent attenuation slope values calculated in step (d);

(f) independently of steps (d) and (e), forming, from the radiofrequency data in respect of each window, a conventional image of the artery in which the intensity (brightness) of each pixel in the image is proportional to the amplitude of the ultrasound echoes received from the corresponding piece of tissue; and

(g) determining whether each average attenuation slope pixel value calculated in step (e) exceeds a predetermined threshold value, or a respective one of a predetermined set of threshold values, and (i) if the, or the lowest, threshold attenuation slope value is not exceeded, displaying the grey scale pixel calculated in step (f) on a conventional output display device of the echoscope; or (ii) if the average attenuation slope pixel value exceeds the threshold attenuation slope value, or a respective one of the predetermined set of attenuation slope threshold values, displaying on said output display device a pixel in a form which is different from the normal image pixel.

12. A method as defined in claim 11, in which said display which is different from the normal image pixel is either (i) a colour which is different from the normal pixel colour, or (ii) a colour which is selected from a plurality of different colours, each of which is representative of a respective range of values of the attenuation slope, between thresholds in a predetermined set of attenuation slope threshold values.

13. A method as defined in claim 11 or claim 12, in which the attenuation slope for each group of spectral characteristic numbers is computed by determining the difference between the spectral characteristic numbers when there are two spectral characteristic numbers in the group, and by calculating the slope of a least squares regression line for the spectral characteristic numbers when there are more than two spectral characteristic numbers per group.

14. A method as defined in claim 11, claim 12 or claim 13, in which said intravascular transducer is moved along the axis of the artery during the performance of the method.

15. Apparatus for detecting and displaying areas of degenerative plaque in an artery of a subject, said apparatus comprising:

(a) reception means for receiving and recording, in digital form, radiofrequency echo signals of ultrasound energy received, by an intravascular ultrasonic transducer that has been positioned at a predetermined location in an artery of a

subject, following transmission of ultrasound by said transducer along a predetermined number of lines of sight;

(b) selection means for selecting a plurality of windows located at a regular spacing down each line of sight and computing, for each window in each line of sight, from the radiofrequency form of the received ultrasound echoes, a spectral characteristic number, the value of which represents the spectral content of echo signals within each window;

(c) computation means for (i) forming the spectral characteristic numbers for each line of sight into groups, each group containing the spectral characteristic numbers in respect of a plurality of adjacent windows, and (ii) computing the attenuation slope for each group;

(d) a digital buffer adapted to receive data from said computation means and to form therefrom an array of pixel values, the value of each pixel in the array corresponding to the average of a number of adjacent attenuation slope values calculated in said computation means;

(e) imaging means for forming, from the radiofrequency data in respect of each window, a conventional image of the artery in which the intensity (brightness) of each pixel in the image is proportional to the amplitude of the ultrasound echoes received from the corresponding piece of tissue; and

(f) comparison means, for determining whether each average attenuation slope pixel value calculated in said digital buffer exceeds a predetermined

threshold value (or a respective one of a predetermined set of threshold values), and if the (or the lowest) threshold attenuation slope value is not exceeded, displaying the grey scale pixel calculated by said imaging means on a conventional output display device of the echoscope; and if the average attenuation slope pixel value exceeds the threshold attenuation slope value (or a respective one of the predetermined set of attenuation slope threshold values), displaying on said output display device a pixel in a form which is different from the normal image pixel display.

16. Apparatus as defined in claim 15, in which said display which is different from the normal image pixel is either (i) a colour which is different from the normal pixel colour, or (ii) a colour which is selected from a plurality of different colours, each of which is representative of a respective range of values of the attenuation slope, between thresholds in a predetermined set of attenuation slope threshold values.

17. A method for use in the detection of calcification of the artery wall of a subject, substantially as hereinbefore described with reference to Figures 1, 2 and 3 of the accompanying drawings.

18. Apparatus for use in the detection of arterial wall calcification in a subject, substantially as hereinbefore described with reference to Figures 1, 2 and 3 of the accompanying drawings.

19. A method for use in detecting and displaying areas of degeneration of plaque in an artery of a subject, substantially as hereinbefore described with reference to Figure 4 of the accompanying drawings.

20. Apparatus for detecting and displaying areas of degenerative plaque in an artery of a subject, as hereinbefore described with reference to Figure 4 of the accompanying drawings.

FIG. 1

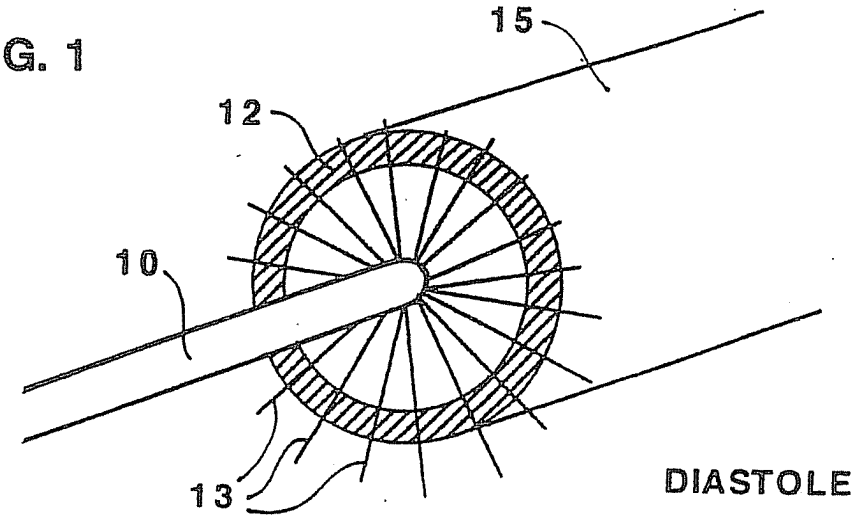
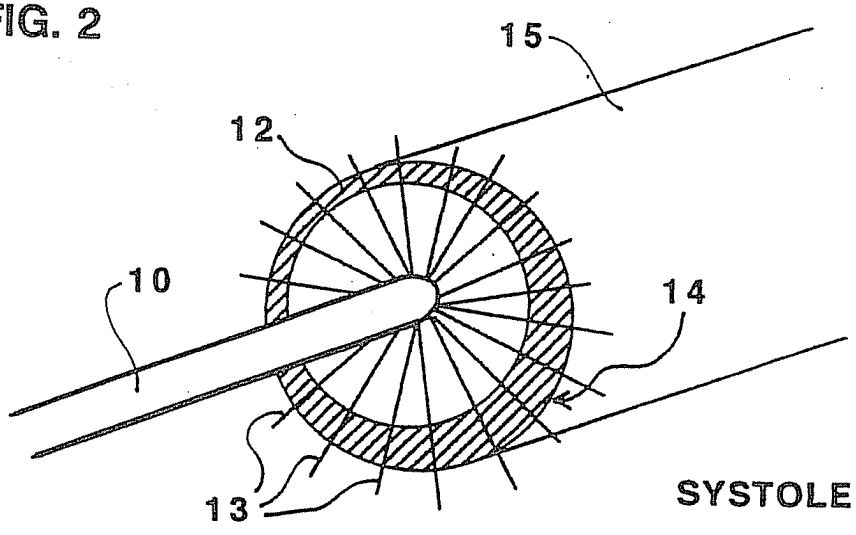


FIG. 2



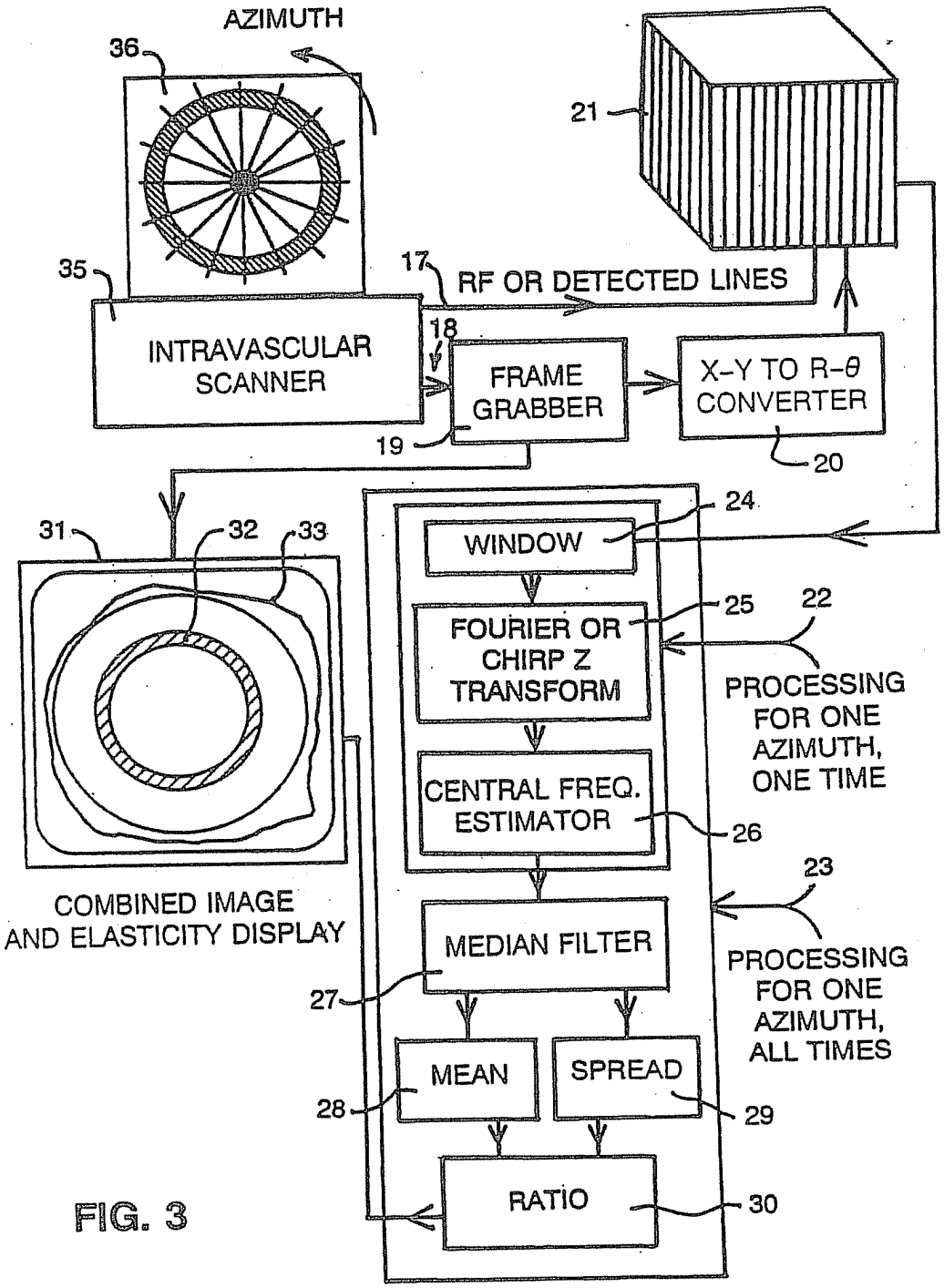

AZIMUTH
36
21
35
17
RF OR DETECTED LINES
INTRAVASCULAR SCANNER
18
FRAME GRABBER
X-Y TO R-θ CONVERTER
19
20
24
31
32
33
WINDOW
25
22
FOURIER OR CHIRP Z TRANSFORM
PROCESSING FOR ONE AZIMUTH, ONE TIME
CENTRAL FREQ. ESTIMATOR
26
23
COMBINED IMAGE AND ELASTICITY DISPLAY
MEDIAN FILTER
PROCESSING FOR ONE AZIMUTH, ALL TIMES
27
MEAN
SPREAD
28
29
RATIO
30

FIG. 3

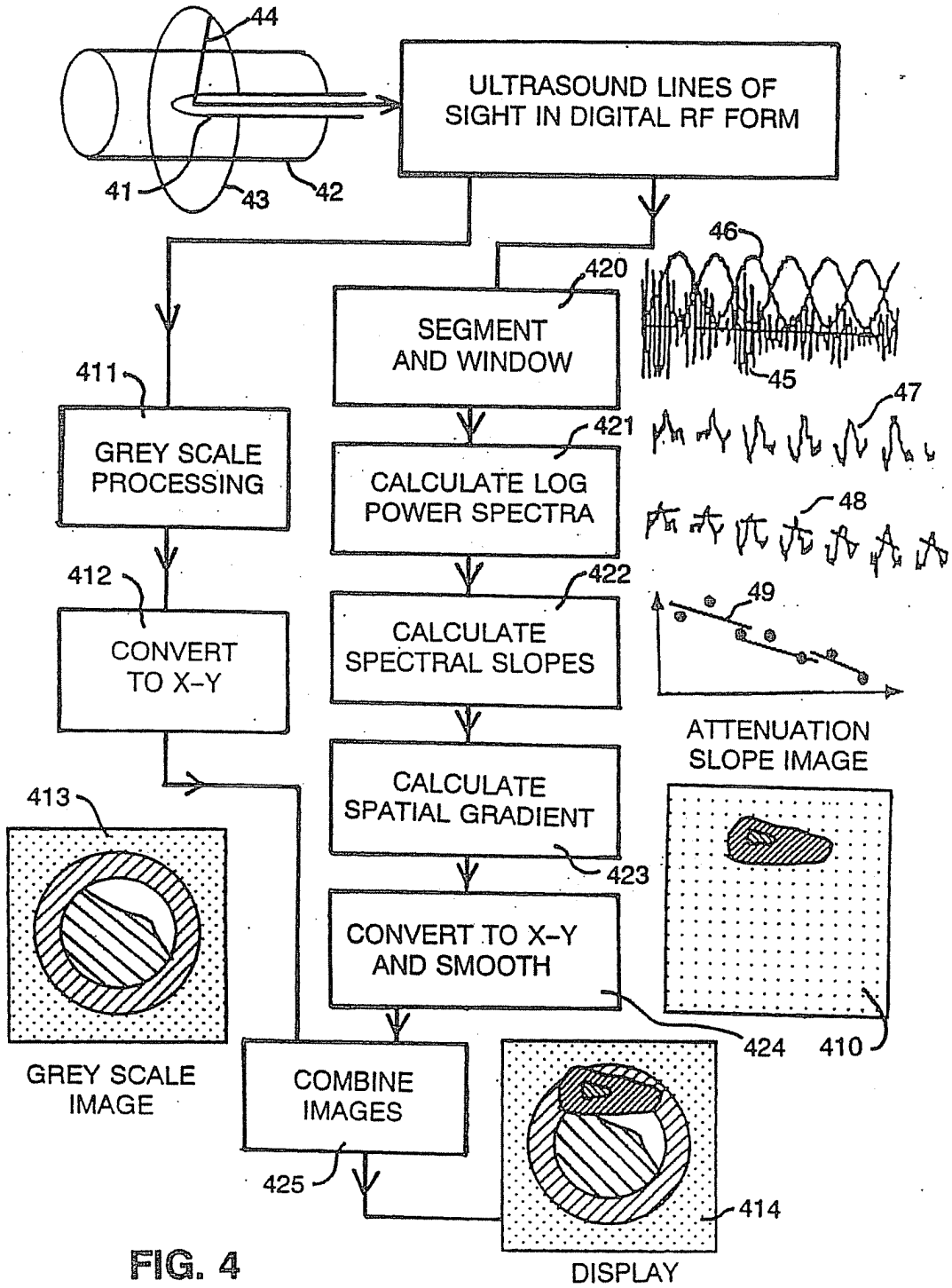

44
41
43
42
ULTRASOUND LINES OF SIGHT IN DIGITAL RF FORM
46
420
SEGMENT AND WINDOW
45
411
GREY SCALE PROCESSING
47
421
CALCULATE LOG POWER SPECTRA
48
412
CONVERT TO X-Y
422
CALCULATE SPECTRAL SLOPES
49
ATTENUATION SLOPE IMAGE
413
CALCULATE SPATIAL GRADIENT
423
CONVERT TO X-Y AND SMOOTH
424
410
GREY SCALE IMAGE
COMBINE IMAGES
425
414
DISPLAY

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU 94/00200

A. CLASSIFICATION OF SUBJECT MATTER
Int. Cl.[5] A61B 8/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC A61B 8/08, 8/12, 8/14, 10/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU:IPC as above

Electronic data base consulted during the international search (name of data base, and where practicable, search terms used)
DERWENT:ULTRASOUND ON A61B 10/00

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	GB,A,1426687 (SIEMENS AKTIENGESELLSCHAFT) 3 March 1976 (03.03.76) page 1 lines 33 to page 2 line 6, page 2 lines 31 to 101, page 3 line 53 to page 4 line 20, page 5 lines 34 to 64	1,2,8,9
X	US,A,4844083 (KABUSHIKI KAISHA TOSHIBA) 4 July 1989 (04.07.89) column 3 line 30 to column 5 line 10, column 6 lines 47 to 65, figures 5 and 6	11-16
A	Patent Abstracts of Japan, C933, page 80, JP,A, 4-17842 (KIYOSHI NAKAYAMA) 22 January 1992 (22.01.92)	1-10

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 June 1994 (30.06.94)	19 July 1994 (19.07.94)

Name and mailing address of the ISA/AU

AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION
PO BOX 200
WODEN ACT 2606
AUSTRALIA

Facsimile No. 06 2853929

Authorized officer

M.FORWARD

Telephone No. (06) 2832606

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	**Citation of document, with indication, where appropriate of the relevant passages**	**Relevant to Claim No.**
P,A	Patent Abstracts of Japan, C1175, page 141, JP,A,5-317313 (KEN ISHIHARA) 3 December 1993 (03.12.93)	1-10
A	WO,A,92/16147 (SCIMED LIFE SYSTEMS INC.) 1 October 1992 (01.10.92) pages 51 to 54, 66 to 68 and 72	8,15
A	WO,A,92/19157 (BRIGHAM AND WOMEN'S HOSPITAL) 12 November 1992 (12.11.92)	8,15
A	US,A,4583184 (TERUMO KABUSHIKI KAISHA) 15 April 1986 (15.04.86)	11-16
A	WO,A,89/04142 (CIRCULATION RESEARCH LIMITED) 18 May 1989 (18.05.89)	11-16
A	US,A,4922422 (PERGRARE) 1 May 1990 (01.05.90)	1-16
P,A	US,A,5307816 (HASHIMOTO ET AL) 3 May 1994 (03.05.94) column 2 lines 31 to 47, column 6 lines 5 to 46	1-16

Box I **Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)**

This international search report has not established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II **Observations where unity of invention is lacking (Continuation of item 2 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

Claims 1 to 10 are directed to detection of calcification of the artery wall, using ultrasonic echos from acoustic discontinuities along radial lines of scan. A ratio indicative of variations in the elasticity of the artery wall is calculated form measurements during each cardiac cycle.

Claims 11 to 16, relate to detection and display of plaque degeneration. The transducer is rotated in the artery and echoes received from a predetermined number of scan lines. Each scan line is broken down to derive an eventual image.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims

2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically

claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
GB	1426687	AT	341644	DE	2319724	FR	2226663
		GB	1426687	NL	168701		
US	4884083	JP	2-136815				
WO	92/16147	EP	529069	JP	5-508099	US	5243988
		CA	2090069	JP	5-344972	NL	190954
WO	92/19157	AU	19949/92	CA	2108910	EP	597864
		IL	101807	US	5203337		
US	4583184	DE	3300834	FR	2522490	GB	2114743
		JP	5-22540				
WO	89/04142	DK	1178/90	EP	386058	GB	2212267
		JP	3-500726	NO	902117	US	5081993
		GB	2246632				
US	4922422	DE	3878011	EP	288115	FR	2514450
		IL	86109	JP	1277753		
US	5307816	DE	4227800	JP	5220152		

END OF ANNEX